

The Influence of Small Concentrations of Air
in Steam on the Steam—Film Coefficient
of Heat Transfer

By
S. J. MEISENBURG

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S. J. MEISENBURG

R. M. BOARTS

W. L. BADGER



Presented at the Twenty-eighth Annual Meeting of the
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THE INFLUENCE OF SMALL CONCENTRATIONS OF AIR IN STEAM ON THE STEAM FILM COEFFICIENT OF HEAT TRANSFER

BY S. J. MEISENBURG * (Non-Member), R. M. BOARTS † (Non-Member)
and W. L. BADGER ‡ (Member)

Presented at the Columbus, Ohio, Meeting, November 13-15, 1935.

A review of the literature concerning the characteristics of steam film coefficients indicates that most of the data have been taken on horizontal tubes.¹⁰ Lately a few investigators have studied the films on vertical tubes. A completely satisfactory method of attack has not yet appeared in the literature, and the effort has generally been to compare the data with the theoretical equation derived by Nusselt:¹¹

$$h_s = \pi \left(\frac{k^3 \rho^2 g r}{L \mu \Delta t} \right)^{0.25}$$

for computing the average steam film heat transfer coefficient where:

h_s = average steam film coefficient over the entire tube.

K = thermal conductivity of condensate.

ρ = density.

g = acceleration of gravity.

r = latent heat of vaporization of condensate.

L = tube length.

μ = viscosity of condensate.

Δt = average temperature difference between surface of metal and steam.

π = a constant (0.943 where all quantities above are in consistent units).

The properties of the condensate film are evaluated at the arithmetic mean of steam and metal surface temperatures, and r is evaluated at steam temperature.

Jakob, Erk and Eck⁶ presented experimental results on condens-

* Shell Petroleum Corp., Wood River, Ill.

† University of Tennessee, Knoxville, Tenn.

‡ University of Michigan, Ann Arbor, Mich.

ing steam on a short vertical tube (1.20 meter). They found that Nusselt's equation gave only fair agreement. Hebbard and Badger⁸ measured the steam film coefficients on a one-inch O. D. vertical tube 12 feet long, operated as a forced circulation evaporator. They took several precautions with their source of steam to insure a supply that was practically air free. They correlated their data with the Nusselt equation and obtained results 34 per cent higher than called for by the theoretical equation.

Kirkbride⁸ correlated data on heat transfer by condensing vapor on vertical surfaces, by means of dimensionless groups, which were suggested by the Nusselt equation. He found that for values of Reynolds number less than 2500 the data checked the Nusselt equation. Above this value the Nusselt equation is no longer valid.

The major portion of the data in the literature on condensing steam on vertical tubes is higher than predicted by Nusselt's theory. Two explanations have been proposed for these results. The first is the occurrence of turbulence in the condensate film. The second is the formation of drops on the condensing surface. This phenomenon was observed by Schmidt, Schurig and Sellschopp¹⁴ who studied the mechanism of the condensation of pure saturated vapor on a vertical wall. They observed two types of condensation, depending upon the condition of the surface of the wall. On a rusty or etched surface the vapor condensed in a continuous film. When a highly polished surface was used the condensate formed in small drops (drop-wise condensation) on the wall. They also found that the condensate would form in drops if the surface was covered with a thin coating of oil. Spoelstra¹⁵ likewise found that the presence of a small quantity of oil would produce drop-wise condensation. The occurrence of drop-wise condensation gave coefficients of heat transfer several times higher than were obtained when film type condensation occurred. The occurrence of drop-wise condensation has recently been investigated by Nagle and Drew¹¹ and Jeffrey and Moynihan⁷ and their results are consistent with the observations of Schmidt, Schurig and Sellschopp. In the light of this work it is rather essential that the condition of the condensing surface be known in any problem involving the study of heat transfer.

None of the investigators mentioned thus far actually determined the amount of air in the condensing steam. This may be a serious omission, since in the derivation of the Nusselt equation one of the restrictions was that the condensing vapor must be pure.

The effect of the presence of air in steam has been discussed by several workers but with no quantitative results. Othmer¹³ was one of the first investigators to give quantitative results with steam containing small percentages of air. His apparatus consisted of a horizontal tube (3-inch O. D. and 47 inches long) inclosed in a small boiler. He used static steam (steam with no velocity past the tube) and varied the air concentration from 0 to 5 per cent by volume. He found that the presence of 0.5 per cent air by volume would decrease the coefficient of heat transfer 50 per cent. Langen⁹ has also presented results obtained in a small apparatus somewhat similar to that of Othmer using static steam.

It is evident that static steam is not the condition met in actual practice. When steam condenses on a heating surface, a layer or film of air is left next to the heating surface. If this layer of air is not disturbed by the scouring effect of currents of steam, then the amount of heat transferred is soon limited to that transmitted by diffusion mechanisms, and the apparatus is said to "air-bind." To prevent this reduction of the steam film coefficient of heat transfer, all heating equipment using condensing vapor is designed to move the air to a venting point. This movement of air is accomplished by sweeping it with steam currents.

Colburn and Haugen² have studied the transfer of heat from a mixture of condensing vapor with a noncondensing gas, and have considered in their treatment the diffusion of steam through the stagnant air film. Their treatment is quite exhaustive, and its application to a given case is complicated. It was hoped that a simple approximation might be found that would be satisfactory for the case where the partial pressure of the noncondensing gas was a small fraction of the total pressure. It was not considered that such an approximation would hold for the general case, but it might represent conditions that occur widely in practice, where steam that contains a small amount of noncondensable gas must be used for heating.

This investigation was undertaken to determine the effect of small concentrations of air in steam on the steam film coefficient of heat transfer on a vertical tube using dynamic (moving) steam.

THE EXPERIMENTAL APPARATUS

Since data were taken simultaneously for two investigations, one concerning the liquid film characteristics and one concerning the steam film characteristics, the requirements for the design of the experi-

mental apparatus were quite rigid.* The apparatus used was an experimental forced circulation evaporator having a single copper tube, 12 feet long, one inch O. D., with a wall $\frac{1}{8}$ inch thick. A diagram of the apparatus is shown in Fig. 1.

The steam used for heating the tube was made from distilled water, which was first boiled in an open vessel to remove as much of the dissolved gases as possible before it was pumped to the boiler. The boiler was heated by closed steam coils. In this manner oil, which promotes drop-wise condensation, was kept from the system. In the case of steam-air mixtures, compressed air was introduced at the boiler. All parts of the evaporator were thoroughly lagged.

Ten copper-constantan thermocouples were installed at 15-inch intervals in the tube wall by the method developed by Hebbard and Badger.⁵ Other thermocouples were used to measure the temperature of the steam jacket, vapor space above the tube, liquor inlet at the bottom of the tube and superheated steam.

The readings of all thermocouples were made with a Leeds and Northrup type K-2 potentiometer.

Samples of steam or steam-air mixtures were withdrawn through small water-cooled condensers at the top and bottom of the steam jacket. In the case of runs made with substantially pure steam, the air concentrations were measured by determining the quantity of oxygen present in the condensed samples by the Winkler method as described by Farmer.³ The oxygen found in the samples was then converted to air concentration. In the case of richer steam-air mixtures, the air concentrations were determined in an apparatus devised by Claassen.¹ The apparatus is illustrated in Fig. 2. *J* and *G* are two 500 cc. burettes, the connecting bottles *K* and *H* are of approximately 600 cc. capacity, and *A* and *B* are two small condensers, one connected to the top of the steam jacket and the other to the bottom. To make a determination of air concentration, the burette *G* and both connecting bottles *K* and *H* were filled with water. The water level on burette *J* was left at some known mark near the bottom. The three-way stopcock *C* was opened to *E* and one of the condensers connected to the point where the sample was to be taken so that the lines were completely flushed out. When the lines were sufficiently flushed, the stopcock *C* was turned so that the sample entered the burette *G*. The air displaced the water which then rose in burette *J*.

* The characteristics of the liquid films will be discussed in a subsequent paper.

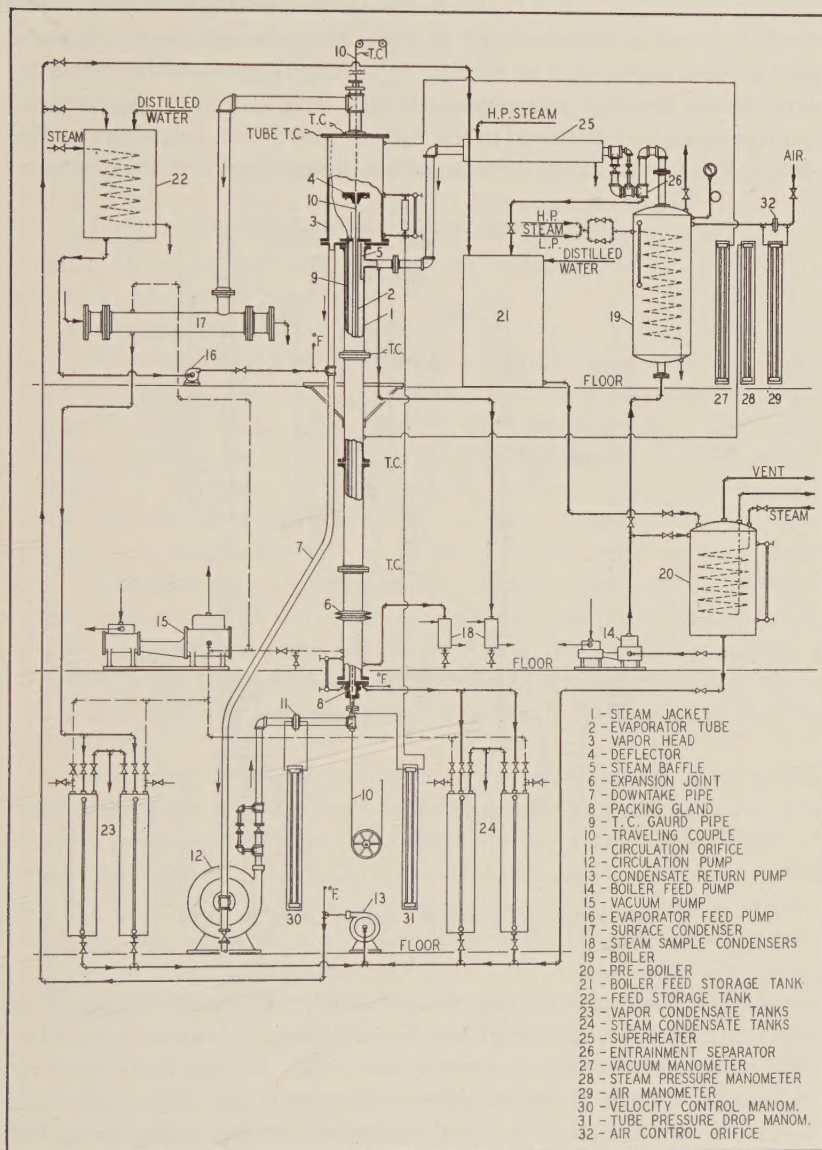
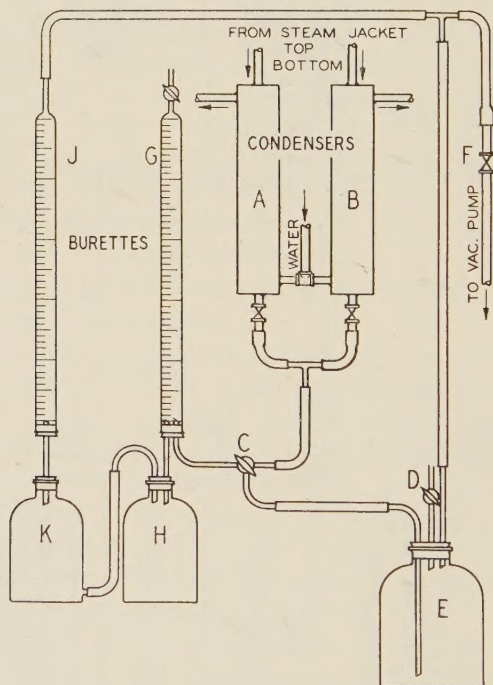


FIG. 1.

When a large enough sample had been withdrawn the stopcock *C* was again turned to *E*. The water levels in the two burettes were then leveled so that each was under an equal pressure and the levels were read in each burette. The reading in burette *G* gave directly the volume of the air that was present in the sample, for no appreciable amount of air was dissolved in the water. Since the temperature of the sample coming from the condenser was determined and the pressure



APPARATUS TO DETERMINE AMOUNT OF AIR IN STEAM

FIG. 2.

was known, the weight of this volume of air could be calculated. The difference between the initial and final reading of burette *J* gave the total volume of the sample (water plus air). To find the volume of water, the volume of air in *G* was subtracted from this difference. Knowing the weight of air and condensed steam, respectively, the percentage of air in the mixture could then be calculated.

All the data were obtained on the transfer of heat to distilled water. The variables and the ranges covered by each were: apparent boiling

point of the solution, 140° to 212° F.; condensing steam temperature, 176° to 248° F.; inlet velocity of liquid, 2.5 to 15 ft./sec.; apparent overall temperature drop, 18° to 72° F.; and inlet air concentration, 0 to 2.0 per cent by weight. Each series of runs was made so that four of the variables were kept constant while the fifth covered the entire range.

Condensate from the steam space was measured in closed calibrated receivers. From the weight of this condensate and the known temperature and pressure of the steam, the total heat input was calculated. This was corrected for loss by radiation, which was determined in a series of blank runs.

The temperature of the steam side of the tube was calculated from the tube-couple readings, the depth to which their junctions were imbedded in the tube wall, and the temperature gradient corresponding to the known rate of heat flow through the tube wall. The steam temperature was taken as the saturation temperature at the partial pressure of the steam, since any small amount of superheat resulting from throttling at the steam inlet would have no measurable effect on the average temperature of the steam in contact with the condensate film. The difference between the steam temperature and the temperature of the outside of the tube was used as the steam film temperature drop. The total heat input (determined as in the previous paragraph) was divided by the outside area of the tube, the steam film temperature drop, and the length of the run. The result is the steam film coefficient, h_s .

The normal length of a single run was 40 minutes. During that time manometer readings were taken every two minutes. All thermocouples were read at least three times during a run. The levels of condensate in the vapor and steam condensate tanks were read at five minute intervals. Samples of steam or steam-air mixtures, whichever the case might be, were taken alternately from the top and bottom of the steam jacket; generally a total of four samples were taken during each run. At all times the steam jacket was freely vented at the bottom to prevent the building up of high air concentrations as in a static system. However, there was always a larger concentration of air at the bottom of the jacket than at the top because of the removal of steam by condensation. For this reason the air concentrations found at the top and bottom were averaged and this value was assumed to be the average concentration of air in the steam jacket and was used in all further calculations. All fundamental data have been tabulated in Table I.

TABLE I.—FUNDAMENTAL DATA (English Units)

Run No.	Steam °F.	Vapor °F.	Liquor Velocity ft./sec.	Wall Temp. (Corr.) °F.	Steam Film, Δt (Corr.) °F.	h_s (Obs.)	% Air by wt.
150	247.60	210.51	2.20	228.73	17.73	1238	.....
151	247.60	210.51	3.40	230.43	16.03	1382	.....
4	247.46	209.59	4.80	228.41	17.89	1249	.....
22	247.77	211.60	5.00	230.62	16.11	1243	.....
149	247.60	210.51	4.90	230.24	16.20	1390	.....
171	247.61	210.32	4.90	230.62	15.85	1386	.....
146	247.67	210.55	5.00	230.00	16.57	1283	0.24
145	247.71	210.55	5.00	228.77	17.90	1134	0.90
140	246.87	210.81	5.00	227.22	18.69	994	1.56
139	246.46	210.85	5.00	226.71	18.81	966	2.81
1	247.69	210.09	9.65	225.12	21.27	1187	.....
5	247.46	209.59	9.60	224.52	21.52	1294	.....
20	247.77	211.80	10.00	223.44	22.62	1303	.....
153	247.60	210.50	9.90	226.01	20.15	1393	.....
147	247.67	210.55	9.90	225.24	21.07	1245	0.20
144	247.71	210.56	9.90	222.28	24.29	912	1.03
141	246.84	210.81	10.00	222.47	23.25	936	1.61
2	247.65	210.41	14.40	221.49	24.58	1240	.....
3	247.54	209.59	14.40	221.39	24.63	1196	.....
152	247.60	210.50	15.00	222.91	23.01	1420	.....
174	247.62	210.34	15.00	222.81	23.17	1370	.....
148	247.67	210.55	15.10	221.71	24.40	1200	0.23
143	247.67	210.52	15.10	219.95	26.40	973	1.13
142	246.95	210.81	15.00	219.48	26.25	907	1.56
136	229.70	212.46	2.40	223.99	5.23	1743	.....
173	229.55	210.34	2.15	222.34	6.69	1533	.....
137	229.85	212.57	3.60	223.80	5.55	1750	.....
23	229.65	211.87	5.00	223.05	6.10	1558	.....
133	229.80	212.40	5.10	222.99	6.29	1667	.....
123	229.78	212.53	5.00	222.48	6.78	1484	0.22
128	229.53	212.15	4.90	221.64	7.43	1195	0.90
168	229.62	212.16	4.90	222.01	7.13	1308	0.63
129	229.26	212.44	4.90	221.62	7.18	1220	1.14
132	228.69	212.37	5.00	220.38	7.93	902	3.48
24	229.65	211.73	10.00	219.09	9.88	1317	.....
52	229.90	211.60	10.00	220.30	8.98	1326	.....
134	229.80	212.40	10.00	220.48	8.64	1538	.....
124	229.28	212.50	10.00	219.76	8.90	1368	0.19
127	229.52	212.03	10.00	218.44	10.50	1064	0.86
130	229.57	212.15	10.00	218.56	10.45	1025	1.37
25	219.60	211.80	15.00	217.73	11.11	1342	.....
135	229.80	212.50	15.00	218.90	10.12	1503	.....
172	229.55	210.34	15.00	217.49	11.16	1555	.....
125	229.64	212.30	15.00	217.93	11.01	1238	0.20
126	229.53	212.09	15.10	217.41	11.50	1040	1.06
169	229.63	212.15	15.00	217.59	11.37	1139	0.72
131	229.27	212.31	15.10	218.31	10.34	1166	1.32

TABLE I (Continued)

Run No.	Steam °F.	Vapor °F.	Liquor Velocity ft./sec.	Wall Temp. (Corr.) °F.	Steam Film, Δt (°F.)	h_a (Obs.)	% Air by wt.
79	247.60	174.99	2.30	219.20	26.74	1204	.....
121	248.19	175.49	3.40	218.30	28.19	1168	.....
78	247.06	175.08	5.00	216.09	29.72	1196	.....
84	247.51	174.64	4.90	213.30	32.45	1050	0.23
83	247.55	174.50	5.00	210.95	34.88	958	1.05
74	247.10	175.94	5.00	210.17	35.76	848	1.66
87	245.67	173.92	5.00	201.71	42.58	632	2.49
80	247.53	174.25	10.00	204.98	40.13	1171	.....
85	247.51	174.46	10.00	201.15	44.04	1025	0.27
81	247.54	174.26	10.00	199.06	46.42	857	1.02
75	247.03	176.08	10.00	198.68	47.21	773	2.08
34	247.92	175.47	15.10	197.71	47.59	1068	.....
77	247.65	174.71	15.00	199.32	45.71	1115	.....
86	247.41	174.23	15.00	194.69	50.12	1006	0.29
82	247.53	174.36	15.10	194.95	50.26	891	1.09
76	246.80	175.92	15.00	193.65	52.06	766	2.84
68	230.15	175.57	2.20	209.26	19.58	1199	.....
120	229.83	175.70	3.30	209.81	18.74	1315	.....
10	229.85	175.09	5.10	204.89	23.48	1223	.....
30	229.40	175.85	5.00	208.25	19.91	1206	.....
67	230.15	175.68	5.00	206.90	21.89	1209	.....
65	229.65	175.35	5.00	205.51	22.86	1089	0.20
63	229.73	174.78	4.95	205.11	23.48	961	0.75
64	228.74	175.53	4.95	201.02	27.68	696	2.61
73	227.93	175.65	5.00	195.07	31.90	589	3.68
9	229.70	176.10	9.95	197.01	30.91	1119	.....
29	229.40	175.85	10.00	197.84	29.85	1117	.....
104	229.60	175.29	10.00	196.70	31.04	1156	.....
66	229.70	174.80	10.00	197.99	30.13	1016	0.23
103	229.64	175.21	10.00	192.21	35.91	817	1.49
102	229.30	175.84	10.00	191.24	37.01	733	2.29
31	229.40	175.85	15.00	192.85	34.61	1089	.....
71	230.06	175.52	15.00	193.62	34.50	1086	.....
70	230.03	175.69	15.00	192.75	35.47	984	0.31
69	230.06	175.47	15.00	191.10	37.38	830	0.73
72	229.36	175.85	15.00	188.33	40.33	692	1.85
101	211.80	175.41	2.30	199.36	11.60	1407	.....
119	211.94	175.36	3.30	198.39	12.68	1344	.....
26	211.73	173.02	5.00	193.83	16.90	1157	.....
100	211.77	175.32	4.95	195.97	14.86	1227	.....
94	211.74	174.87	4.95	195.59	15.21	1194	0.16
95	211.93	175.39	5.10	193.44	17.61	958	1.13
89	211.47	174.08	5.00	189.94	21.05	764	3.79
88	210.53	174.04	5.10	187.80	22.03	613	4.35

TABLE I (Continued)

Run No.	Steam °F.	Vapor °F.	Liquor Velocity ft./sec.	Wall Temp. (Corr.) °F.	Steam Film, Δt (Corr.) °F.	h_a (Obs.)	% Air by wt.
56	211.80	175.47	10.00	191.76	18.92	1138	.....
99	211.08	175.30	10.00	189.81	20.73	1187	.....
93	211.84	174.78	10.00	189.22	21.38	1127	0.16
96	211.87	175.10	10.00	187.52	23.23	926	0.93
90	211.47	173.92	9.95	185.59	25.21	775	2.34
13	211.60	174.97	15.00	185.90	24.02	1362	.....
58	211.80	175.60	15.00	185.61	21.73	1127	.....
98	211.83	175.08	15.00	186.62	23.75	1187	.....
92	211.80	174.11	15.10	185.29	25.13	1069	0.42
97	211.37	175.18	15.05	184.81	25.82	932	1.27
91	211.43	174.69	15.10	183.15	27.51	798	3.19
114	193.70	175.56	2.30	183.17	5.13	1529	.....
167	193.32	174.71	2.20	187.42	5.50	1426	.....
176	193.43	174.76	2.20	187.87	5.14	1604	.....
118	193.80	175.36	3.30	188.13	5.27	1452	.....
166	193.45	174.84	3.30	187.38	5.67	1383	.....
39	193.46	175.85	4.95	188.14	5.00	1270	.....
115	193.80	175.36	4.90	186.62	6.70	1394	0.18
122	193.31	174.96	5.00	185.70	7.15	1272	0.27
108	194.03	176.43	5.00	186.17	7.40	1197	0.99
113	193.69	175.93	5.00	184.44	8.98	823	1.69
138	193.65	175.37	5.00	182.32	11.01	549	3.44
38	193.64	175.85	10.05	184.20	8.86	1273	.....
116	193.70	175.31	10.00	183.49	9.61	1227	0.22
106	193.96	176.05	10.00	183.76	9.62	1189	0.34
109	194.14	176.47	10.00	183.10	10.48	1065	0.96
112	193.65	175.69	10.00	181.23	12.11	746	1.73
40	193.46	175.73	15.10	181.58	11.22	1150	.....
117	193.75	175.41	15.00	181.96	11.09	1220	.....
715	193.43	174.92	15.00	181.72	11.10	1224	.....
105	193.96	176.14	15.00	181.93	11.37	1145	0.41
110	194.20	176.30	15.10	181.57	12.01	1008	1.13
111	193.46	175.85	15.05	180.24	12.95	776	1.44
156	211.84	139.77	2.30	190.29	20.27	1230	.....
157	211.86	139.72	3.40	186.31	24.11	1155	.....
36	211.80	138.87	5.00	170.42	39.20	1077	.....
170	211.87	139.82	4.80	181.43	28.70	1178	.....
154	212.17	138.79	9.90	168.15	41.78	1073	.....
155	211.77	139.67	15.00	162.70	46.39	1116	.....
159	193.63	139.51	2.30	177.54	15.15	1204	.....
160	193.60	139.27	3.30	174.53	18.08	1081	.....

TABLE I (CONTINUED)

Run No.	Steam °F.	Vapor °F.	Liquor Velocity ft./sec.	Wall Temp. (Corr.) °F.	Steam Film, Δt (Corr.) °F.	hs (Obs.)	% Air by wt.
43	192.64	139.67	5.00	171.35	26.25	1005	.....
41	192.55	138.07	9.95	158.51	32.42	953	.....
42	192.64	139.67	10.00	159.15	31.97	918	.....
44	192.55	139.93	14.00	153.39	37.54	838	.....
158	193.54	139.88	15.00	155.60	36.16	957	.....
162	175.59	139.83	2.30	163.79	11.20	1038	.....
163	175.34	139.11	3.40	161.40	13.28	964	.....
47	175.73	139.93	5.00	159.77	15.24	904	.....
61	175.25	138.84	4.80	158.51	15.96	948	.....
45	175.85	139.14	9.95	151.55	23.34	792	.....
46	175.60	139.40	10.60	152.39	22.21	876	.....
164	175.26	138.97	9.90	152.23	22.01	890	.....
48	175.73	139.93	14.90	150.25	24.40	858	.....
165	175.19	139.17	15.00	149.10	25.01	841	.....

CORRELATION OF THE DATA

The data were correlated in two steps: First, the correlation of the air-free runs, and second, the correlation of the runs containing air.

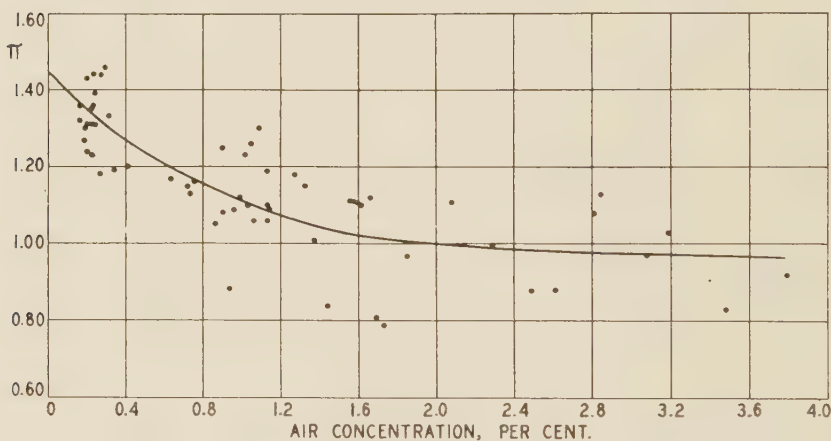
In the case of substantially air-free steam, the data have been compared with the theoretical Nusselt equation. This was done by calculating the constant π of the equation for each run. The average value of the constant was found to be 1.440, which is 53 per cent higher than that called for by the theoretical Nusselt equation. When the coefficients were calculated using the Nusselt equation with this new constant, the deviations between the calculated and observed values were in most cases less than ± 10 per cent.

The data obtained in runs in which small percentages of air were present were correlated by two methods: First, by a direct comparison with the Nusselt equation; second, by the derivation of an empirical equation.

By the first method the data were compared directly with the Nusselt equation in the same manner used in calculating the runs made

with air-free steam. In this case the calculated values of the constant were then plotted against the air concentrations (C) for each run (Fig. 3). When the coefficients h_s were calculated using the Nusselt equation with different values for the constant (depending on the air concentration) taken from this curve, the deviations between the calculated and observed values were, in nearly all cases, less than ± 10 per cent.

The second method consisted of a correlation by means of an empirical equation. With the apparatus as described and the operat-



EFFECT OF AIR ON THE CONSTANT π IN THE NUSSULT EQUATION.

FIG. 3.

ing conditions as defined, it was assumed that the values of the steam film coefficient when air was present depended upon:

- (1) The air content of the steam-air mixture, C .
- (2) The temperature of the condensing steam in the steam jacket, T .
- (3) The temperature drop from the condensing steam to the tube wall, Δt .

The effect of these variables was determined empirically from the data. This was accomplished by plotting the experimental values of $\log \Delta t$ against $\log h_s$ for a constant condensing temperature and constant air content. A plot of this type is shown in Fig. 4. From this figure it is to be seen that a straight line is a reasonable correlation for

the points representing the runs having approximately the same air content. This indicates that with constant air content and constant condensing temperature the logarithm of the steam film coefficient is a linear function of the logarithm of the temperature drop and can be expressed by:

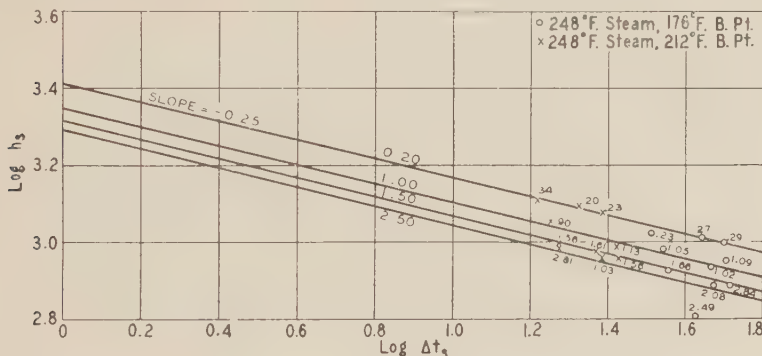
$$h_s = A(\Delta t)^x$$

Where

A = intercept of the line.

x = slope of the line.

A plot of this type was made for each condensing temperature. In all cases the best line drawn through the points representing approxi-



EFFECT OF Δt_s UPON h_s

FIG. 4.

mately constant air content had a slope of -0.25 . The values of the intercept (A) changed for each change of air content (C) or condensing temperature (T).

The values of $\log A$ were then plotted against the experimental values of $\log C$, where C is expressed as fraction of air in the steam-air mixture, as shown in Fig. 5. Here there are hardly enough points absolutely to define a curve. However, it would seem that the straight lines drawn through the points are reasonable, and hence,

$$A = B(C)^y$$

Where

B = intercept of the line.

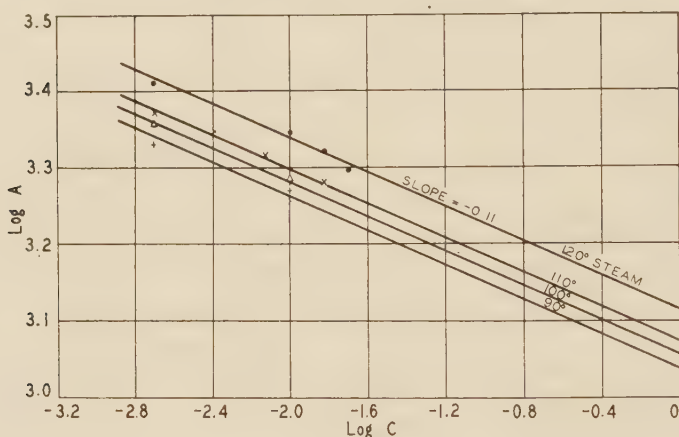
y = slope of the line.

The lines have been drawn parallel and with a slope of -0.11 .

The effect of temperature drop and air concentration on the coefficient can then be expressed mathematically by:

$$h_s = B \left(\frac{1}{\Delta t} \right)^{0.25} \left(\frac{1}{C} \right)^{0.11}$$

The only known variable remaining is the temperature of the condensing steam (T) which defines the value of the constant B . It



EFFECT OF AIR CONCENTRATION UPON A

FIG. 5.

was impossible to determine the value of B empirically with the available data. However, by comparing the empirical equation with the Nusselt equation the similarity of the two is apparent at once. First, the temperature drop Δt appears in the two equations with the same exponent. Second, the value of B in the empirical equation is dependent on the condensing temperature of the steam and this in turn evaluates the effect of viscosity, density, and thermal conductivity of the condensate, and the latent heat of condensation. For these reasons the factor representing the air was added to the Nusselt equation. This could be done without affecting the dimensions of the equation, since C is a ratio and dimensionless. The modified Nusselt equation then became:

$$h_s = \pi \left(\frac{k^3 \rho^2 g r}{L \mu \Delta t} \right)^{0.25} \left(\frac{1}{C} \right)^{0.11}$$

The observed values of h_s for each run were substituted in this equation and the value of the constant π determined. The average value of π for all runs containing air was 0.670.

When the coefficients were recalculated with this equation, the deviation between the calculated and observed values was less than ± 10 per cent in 90 per cent of the runs.

DISCUSSION OF RESULTS

While some results have been reported which indicated higher values than these for the steam-film coefficients, when pure steam had been used as the condensing vapor, this can possibly be accounted for

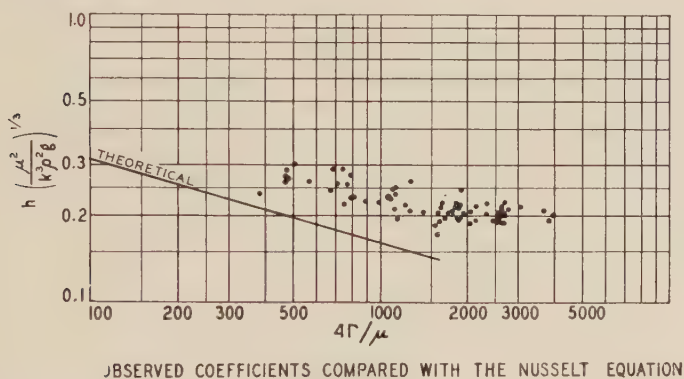


FIG. 6.

by the following reasons. First, the possibility of drop-wise or combined drop-wise and film-type condensation in some of the previous work may have caused higher results. When this experimental evaporator was first assembled the copper tube had been polished to almost a mirror finish. Since this surface would not be permanent, the apparatus was operated for several days to oxidize the surface of the tube. The tube was then removed from the steam jacket and examined. It was covered with a very thin coating of oxide. Upon dropping a small quantity of distilled water on it the water immediately spread into a film, indicating that the surface was wettable and would produce film-type condensation. From time to time similar observations were made to determine if film-type condensation still obtained. It did. However, it is realized that the above test, made when the

apparatus was not operating, cannot be depended upon absolutely to indicate conditions when operating.

Second, the possibility of turbulence in the condensate film would tend to increase the coefficient. To determine which probable type of flow was obtained in this investigation, the results have been plotted in Fig. 6 by the method of Kirkbride. The points lie in a band parallel to the line representing the Nusselt equation, but slightly higher. Since it is not likely that turbulence exists below a value of 2500 for Reynolds number ($4C/\mu$) most of this work must have been in the viscous range.⁸

Third, the method of measuring tube wall temperatures used in this investigation (which gave very consistent results) indicates larger temperature drops across the steam film than the data obtained by other methods, under like conditions. This operates to lower the observed value of the steam-film coefficient.

The two methods developed for determining the coefficient when air is present are equally reliable (± 10 per cent). The use of the curve (Fig. 3) in the first method is perhaps the simpler of the two, since it does not involve any new factor in the Nusselt equation. The equation developed for determining the coefficient in the case of steam containing small percentages of air is very similar to the one derived for pure steam, and is

$$h_s = 0.670 \left(\frac{k^3 \rho^2 g r}{L \mu \Delta t} \right)^{0.25} \left(\frac{1}{C} \right)^{0.11}$$

It can be used for steam containing 0.10 to 4.00 per cent air by weight.

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